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COMPARISON OF THE VIPER PULSED FUSION ROCKET TO PRIOR FUSION SPACE PROPULSION DESIGNS

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Abstract

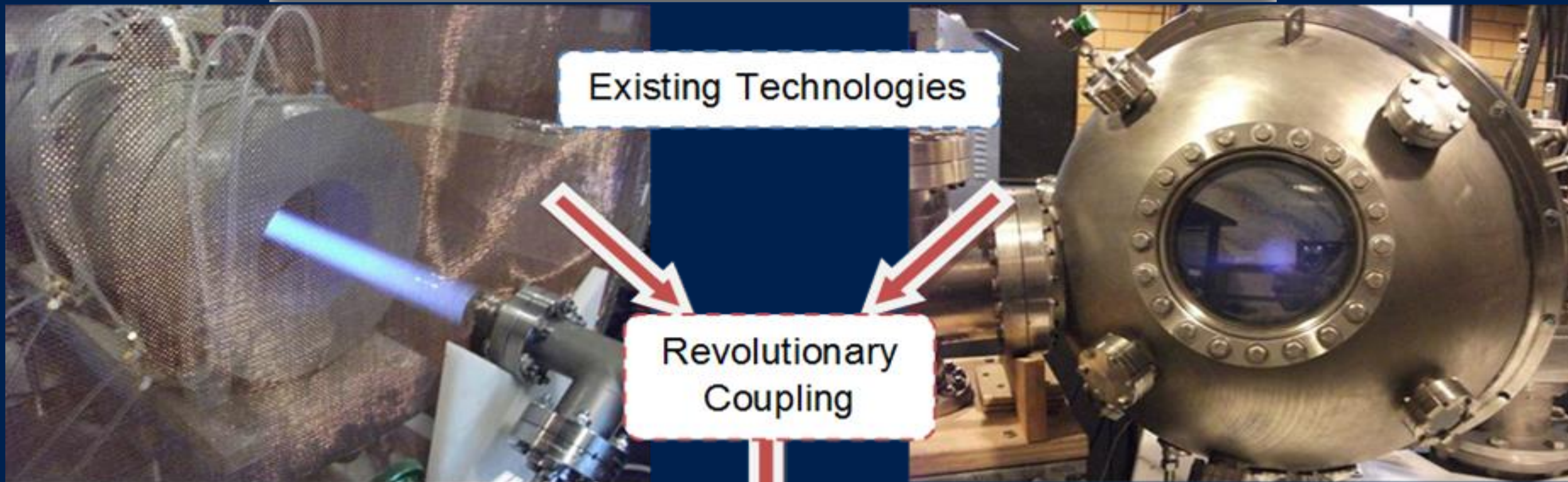
– Fusion power systems have the potential to provide unparalleled power budgets to a spacecraft's propulsion system, life support system, and electronics. Fusion power can be used directly to super heat propellant for thrust or, the energetic fusion products can be used as propellant. Some of these systems are operated strictly under steady-state conditions for long-duration continuous power out-put. Others are designed for short-burst pulsed operation and hence are known as nuclear pulsed propulsion. A series of these fusion bursts can be used to propel the spacecraft, charge power systems, or both. There are also fusion propulsion concepts that utilize a combination of these mechanisms. A preliminary design study of a new nuclear pulsed propulsion concept called the Viper Pulsed Fusion Rocket [Orcutt, et. al.]. In this presentation VIPER will be compared to previously published fusion space propulsion concepts. The process identifies the requirements of fusion-class systems, and discusses operational parameters such as specific power, specific impulse, and nozzle jet efficiency.

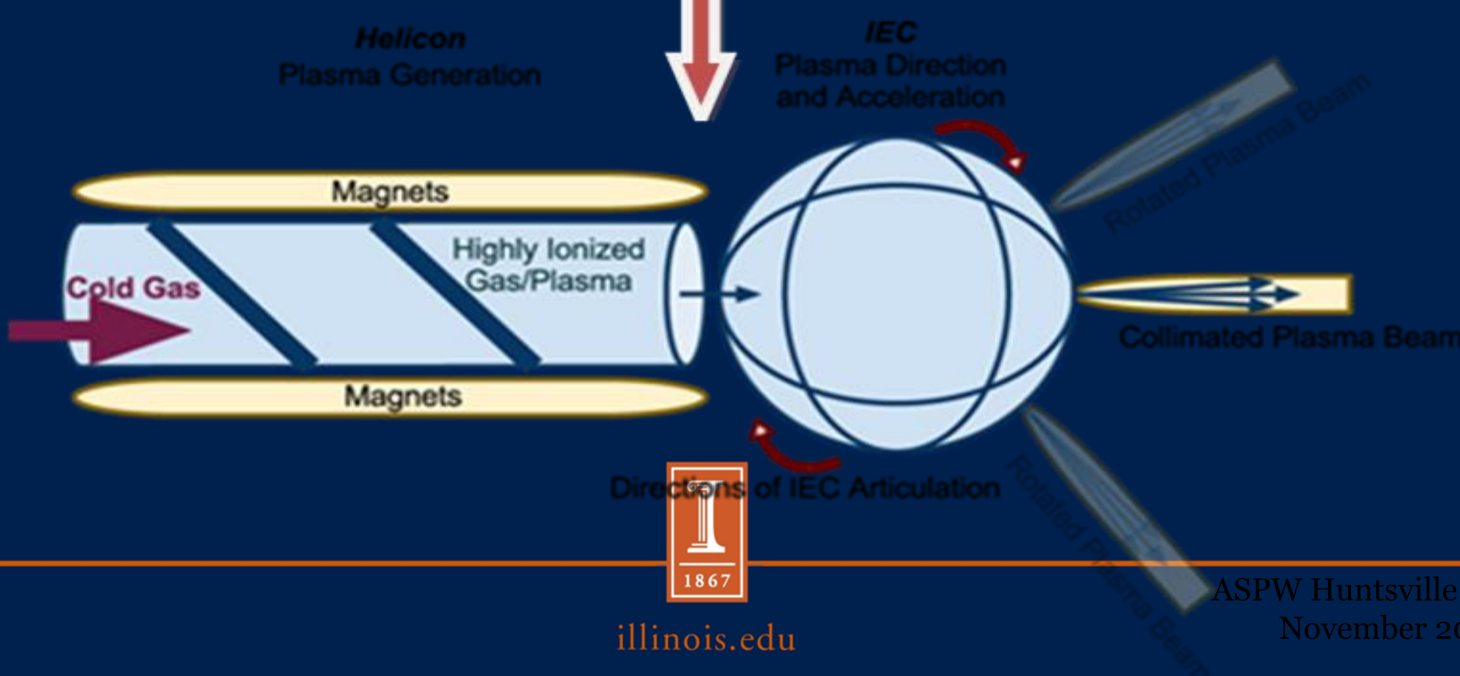
Introduction to HIIPER

- Helicon-injected IEC-Class Plasma Thruster
- Designed for interplanetary and deep space missions
- Highly Scalable (Variable specific impulse)
- Compact
- Simple design using commercially available helicon and IEC device
- Gas Versatile
- Reduced erosion of grid and plasma facing components – higher operational lifetime
- Highly efficient due to nearly complete ionization of propellant by the Helicon source

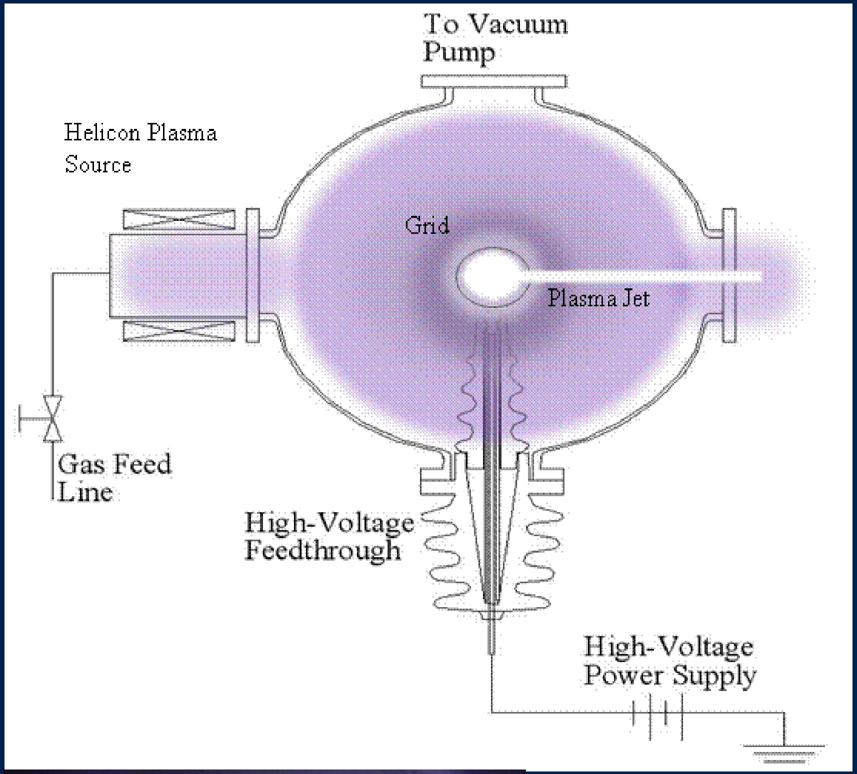
Viper is an extension of “HIIPER” which is an experiment we are presently working on for EP

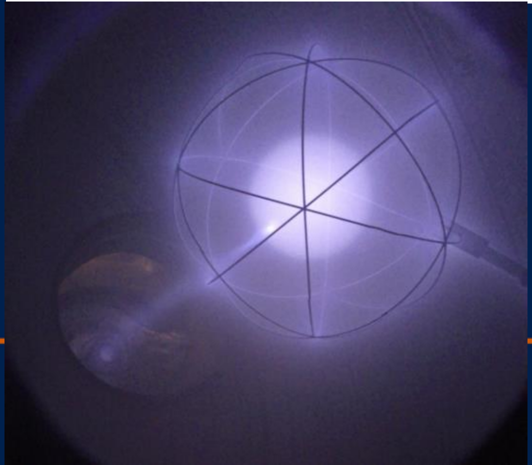
Introduction to HIIPER





Introduction to HIIPER





- High density plasma is produced by the Helicon source
- Inertial electrostatic confinement accelerates plasma using a spherical diode configuration
- A thin plasma beam is produced due to asymmetry in the central cathode grid in “jet mode” operation.
- This plasma jet contains a significant fraction of the input energy

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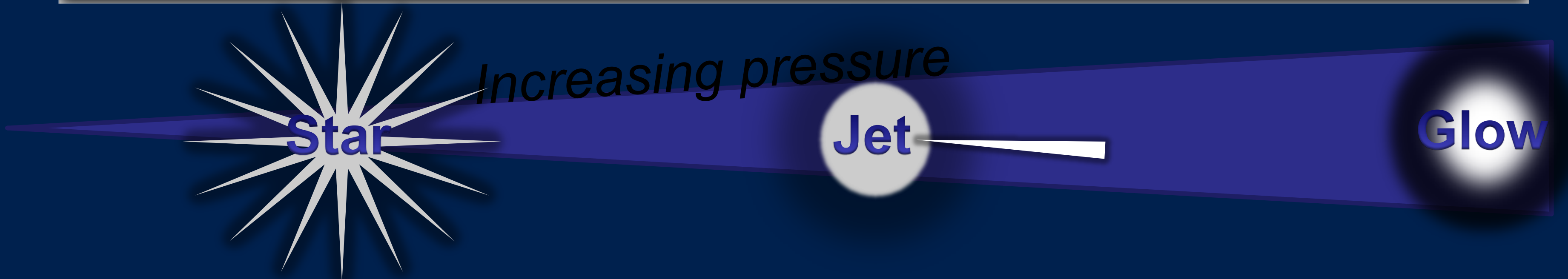
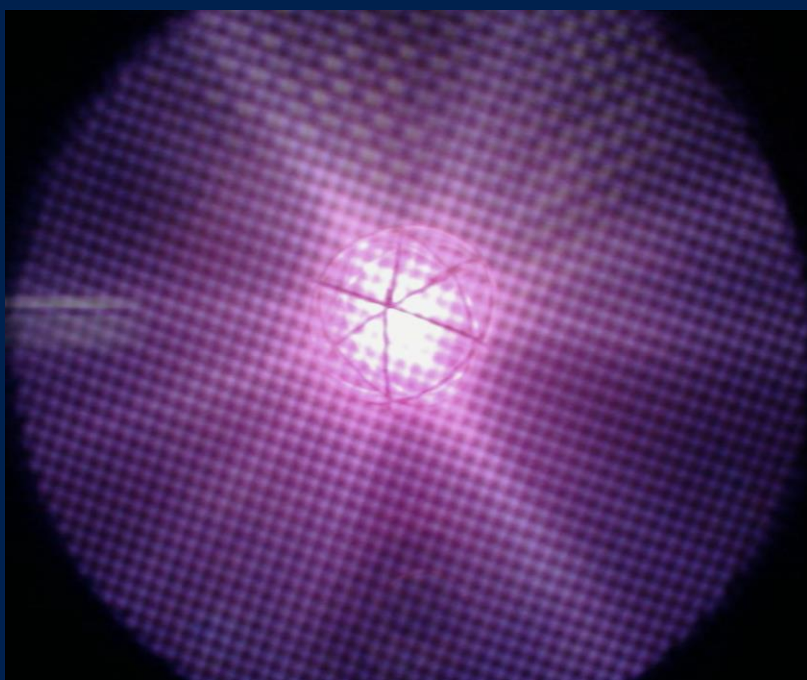
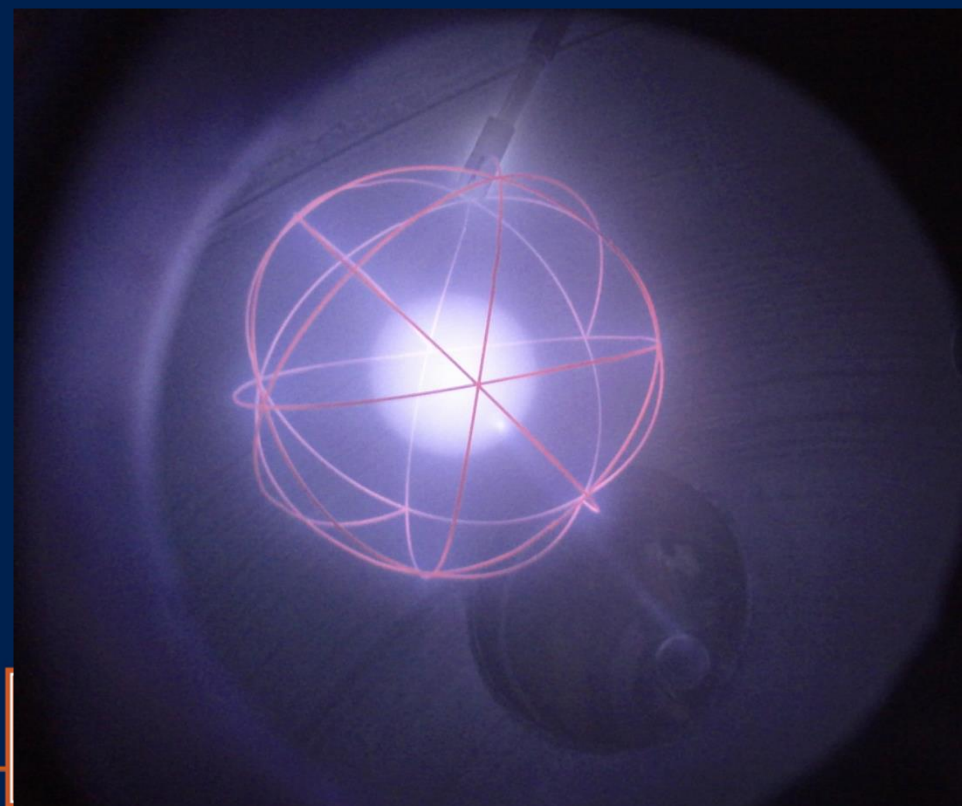
Background – IEC Operation Modes







Overview of Prior Fusion Space Propulsion Concepts

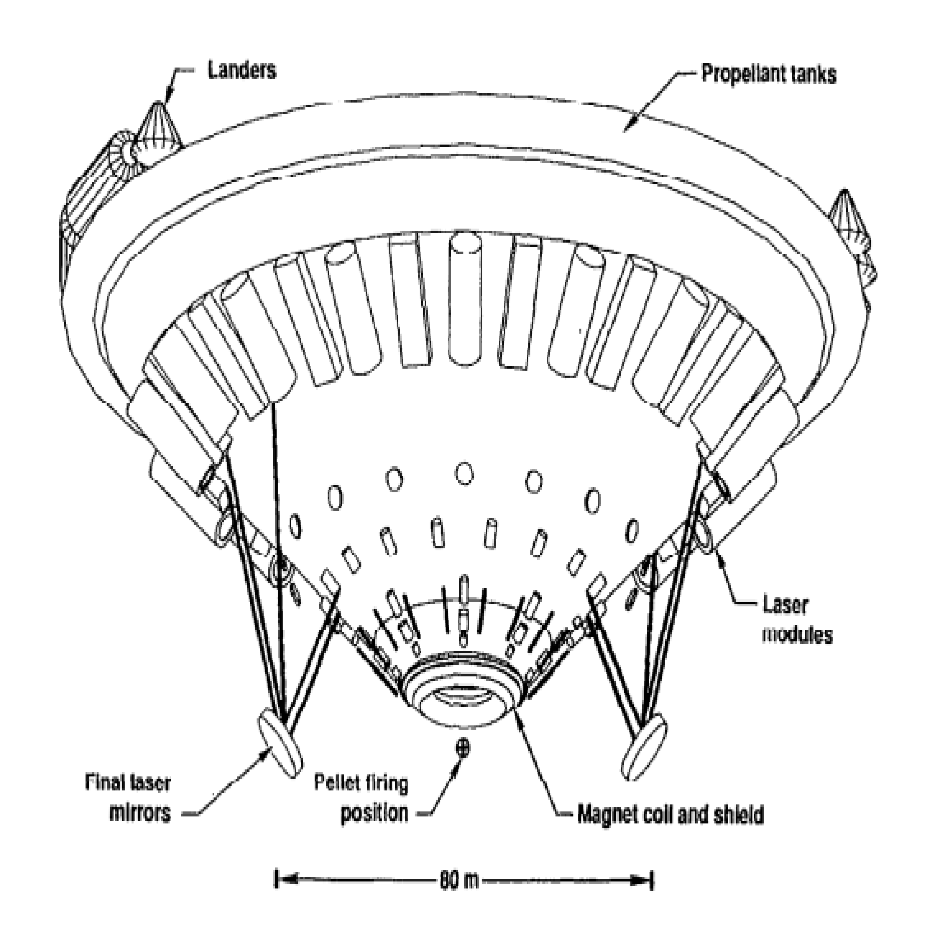
Concepts surveyed by Craig H. Williams (NASA Glenn), 1997:

1. Borowski (1987)	Spherical Torus
2. Borowski (1987)	Spherical Torus
3. Borowski (1987)	Spheromak
4. Carpenter, et al. (1992)	Thermal Barrier Tandem Mirror
5. Santarius (1992)	Tandem Mirror
6. Nakashima, et al. (1994)	Field Reversed Mirror
7. Kammash, et al. (1997)	Gasdynamic Mirror
8. Emrich (1995)	Gasdynamic Mirror
9. Teller, et al. (1991)	Dipole
10. Bussard (1993)	Electrostatic Confinement
11. Orth, et. al. (1987)	Inertial Confinement
12. Hyde (1983)	Inertial Confinement
13. Smith, etal. (1997)	Antimatter Cat. Microfission/Fusion

Concepts of Interest

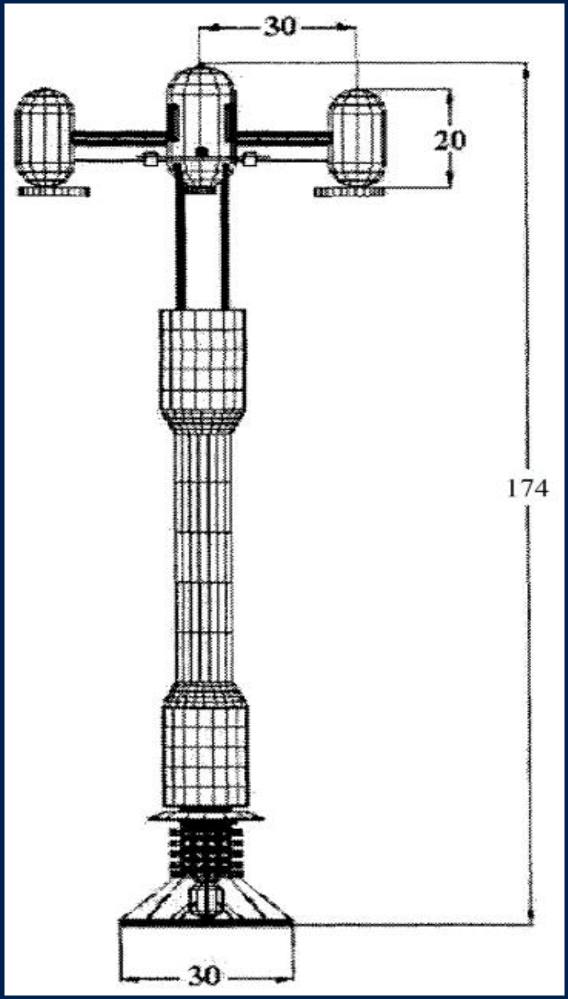
VISTA

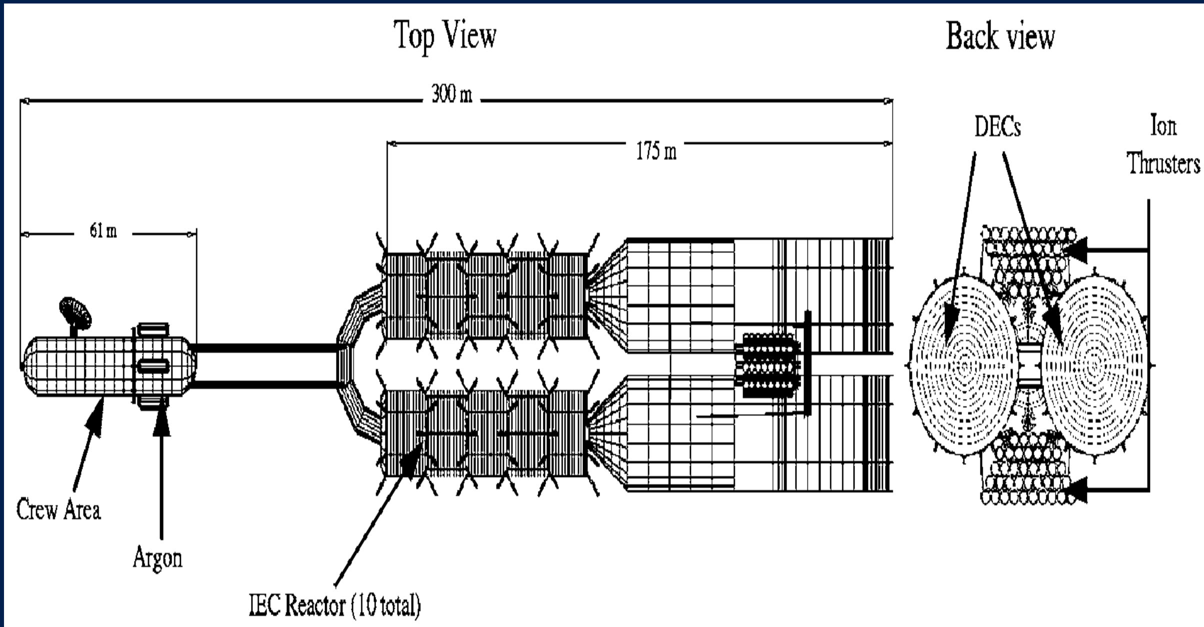
- Uses laser system to irradiate ICF targets
- A 12-Tesla warm superconducting magnet used to focus the plasma into a plume for thrust
- Only 4% neutron emissions strike the spacecraft
- An option of Variable Impulse by varying the amount of expellant
- An advanced fast ignition (FI) mechanism known as block ignition was studied by Miley et al. as an application to the VISTA concept.



C. D. Orth, 1998

IEC based concepts: Fusion Ships I & II





Fusion Ship II, Miley, 2003

Fusion Ship I,
Miley, 2002

Fusion Ships I & II

	Fusion Ship I	Fusion Ship II
Overall Mass (Metric T)	500	500
Overall Length (m)	174	300
Number of crew	10	10
Thrust Power (MW)	86	750
Reactor Gain	4	9
Reactor Power (MW)	296	2178
Thrust system	Krypton ion	Argon ion
Specific impulse (sec.)	16000	35000
Jupiter one way trip time (days)	400	210

Disadvantages in prior concepts

- Complexity of design
- Since these were manned concepts, the radiation protection added a lot of weight
- Use of D-D and D-T fusion led to neutron flux and related radiation hazards
- Inefficient method of thrust production since DECs were used instead of Direct Thrust conversion.

Prior fusion propulsion studies were for manned missions while VIPER is a unmanned probe for deep space scientific exploration.

Manned missions vs. Unmanned missions

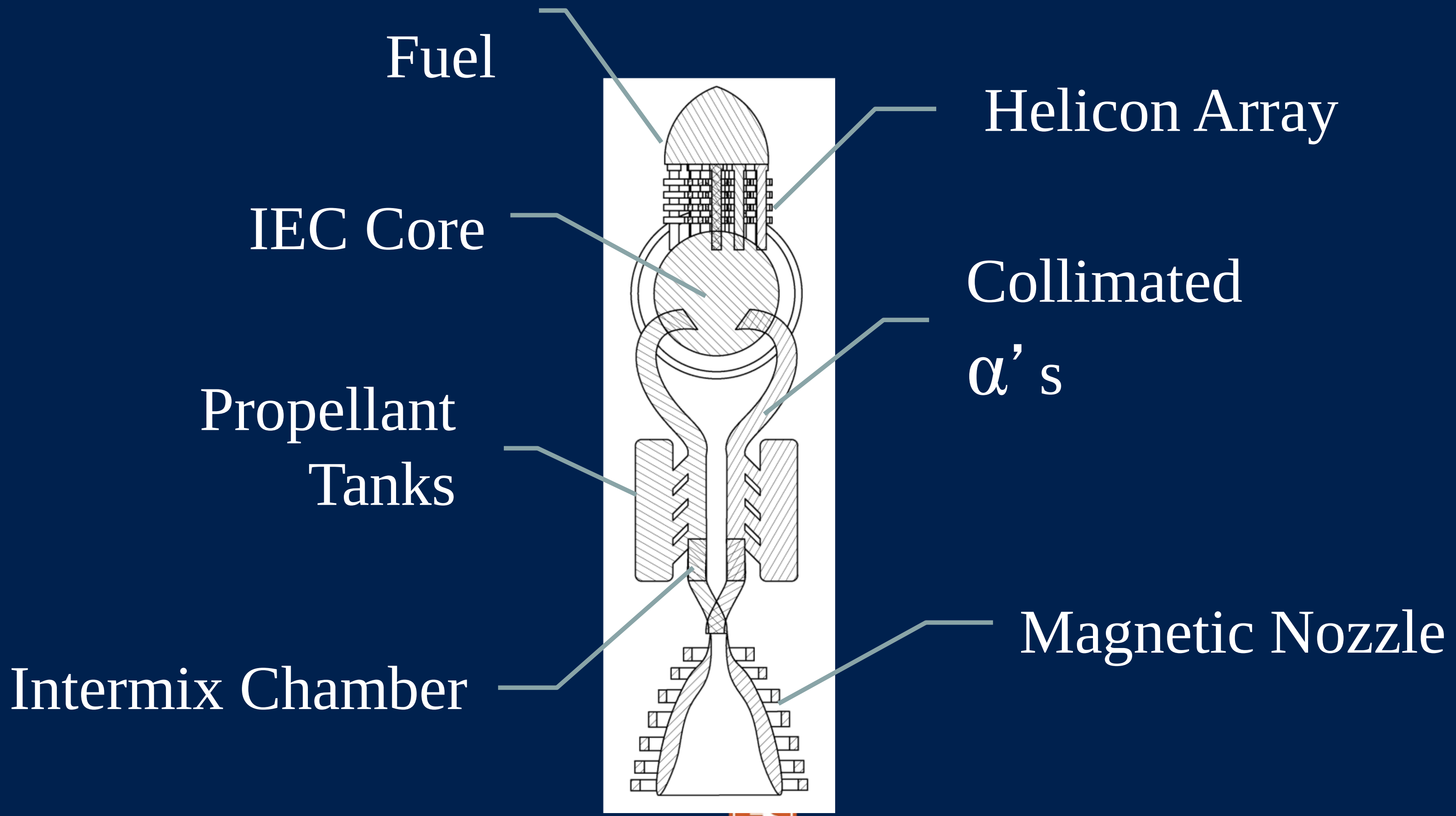
- More probe type missions are expected in the future
- Probe missions to date have generally been very successful, but require very long trip times for outer space mission
- VIPER was designed to use fusion propulsion to significantly reduce trip times.

Mission capabilities

- Shorter time period
  - ✓ *Pluto arrival < 1 year*
  - ✓ *Sedna (518 AU) arrival < 5 years*
  - ✓ *200 MT cargo to Mars ~ 120 days*

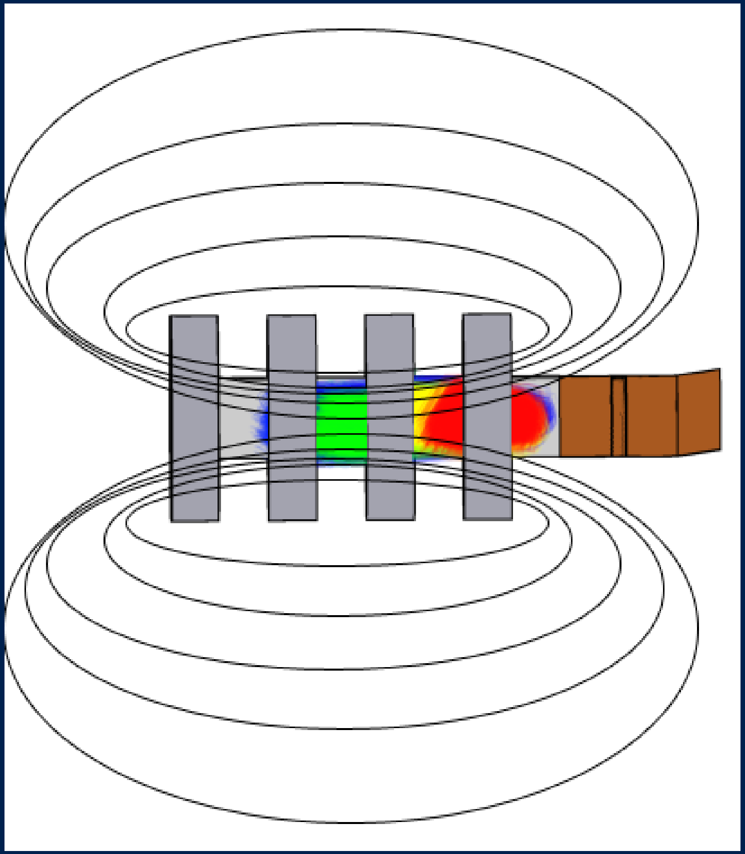
- Reusable probe
  - ✓ *Extremely high ΔV allowing maneuverability, orbital transfers, sample return, etc.*

VIPER Schematic



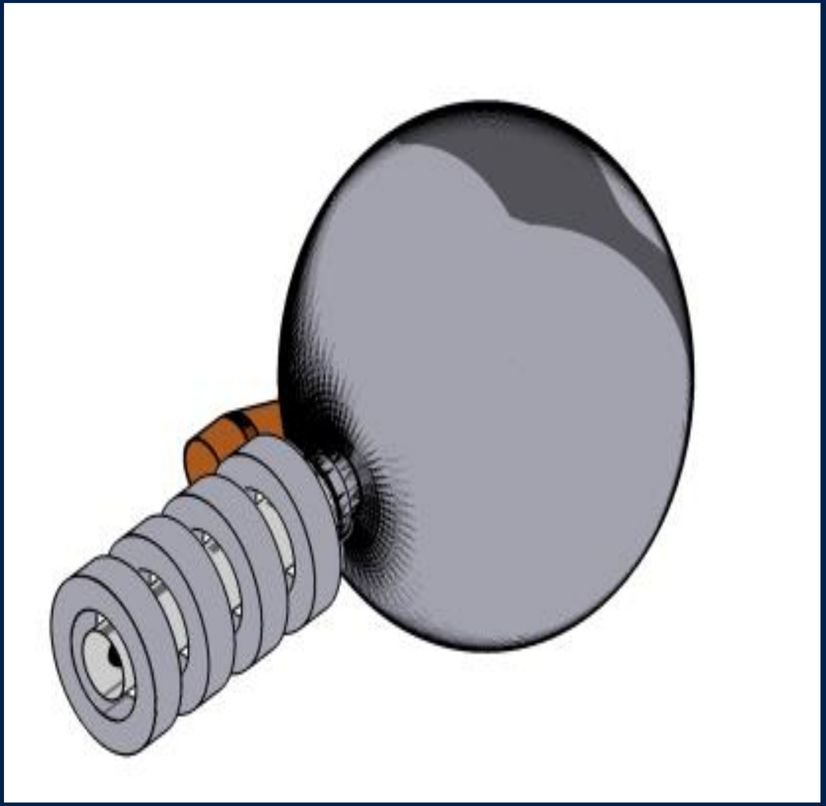
Helicon – Fusion Plasma Source

- RF-heated plasma
- Pulsed power ($\leq$ 1 ms)
- Efficient (~98%) high density neutral plasma (10^{17} cm^{-3})
- Optimal fusion plasma delivery system



Inertial Electrostatic Confinement

- Spherical electrostatic potential trap
- Developed for fusion in 1960's
- Prior shortcomings in confinement & plasma density
- Helicon-fed design is currently under evaluation at Univ. of Illinois (this is an experimental electric propulsion system called HIIPER)

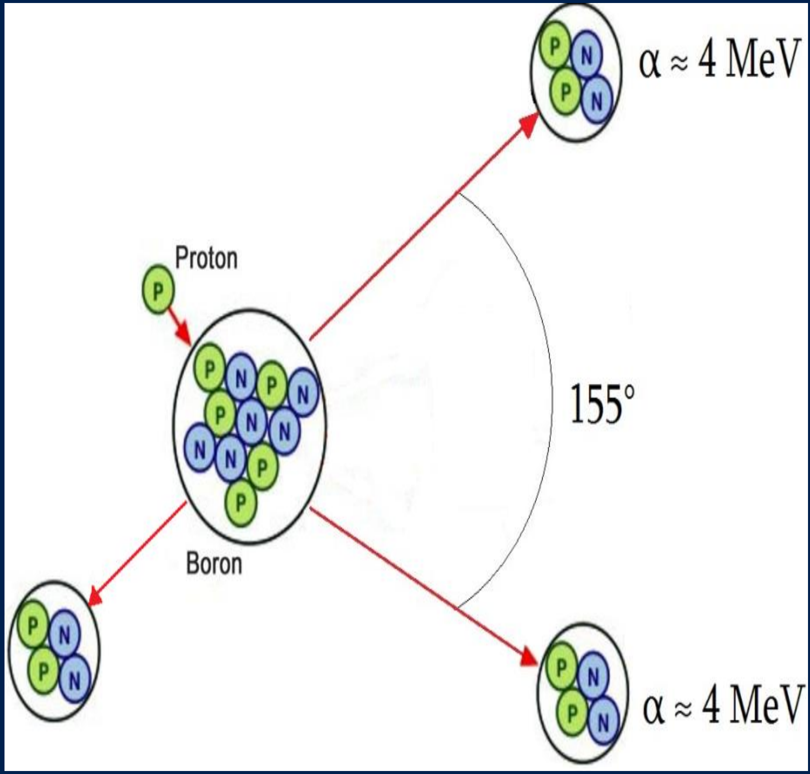


Salient features of VIPER

- Fusion conditions needed for p-^{11}B have been achieved in IEC previously
- Breakeven cathode power est. @ ~80 A 170 kEV
- Power produced = 360 MW
- Bremsstrahlung can be resolved through thermal & spatial plasma stratification
- Realizable near-term technology

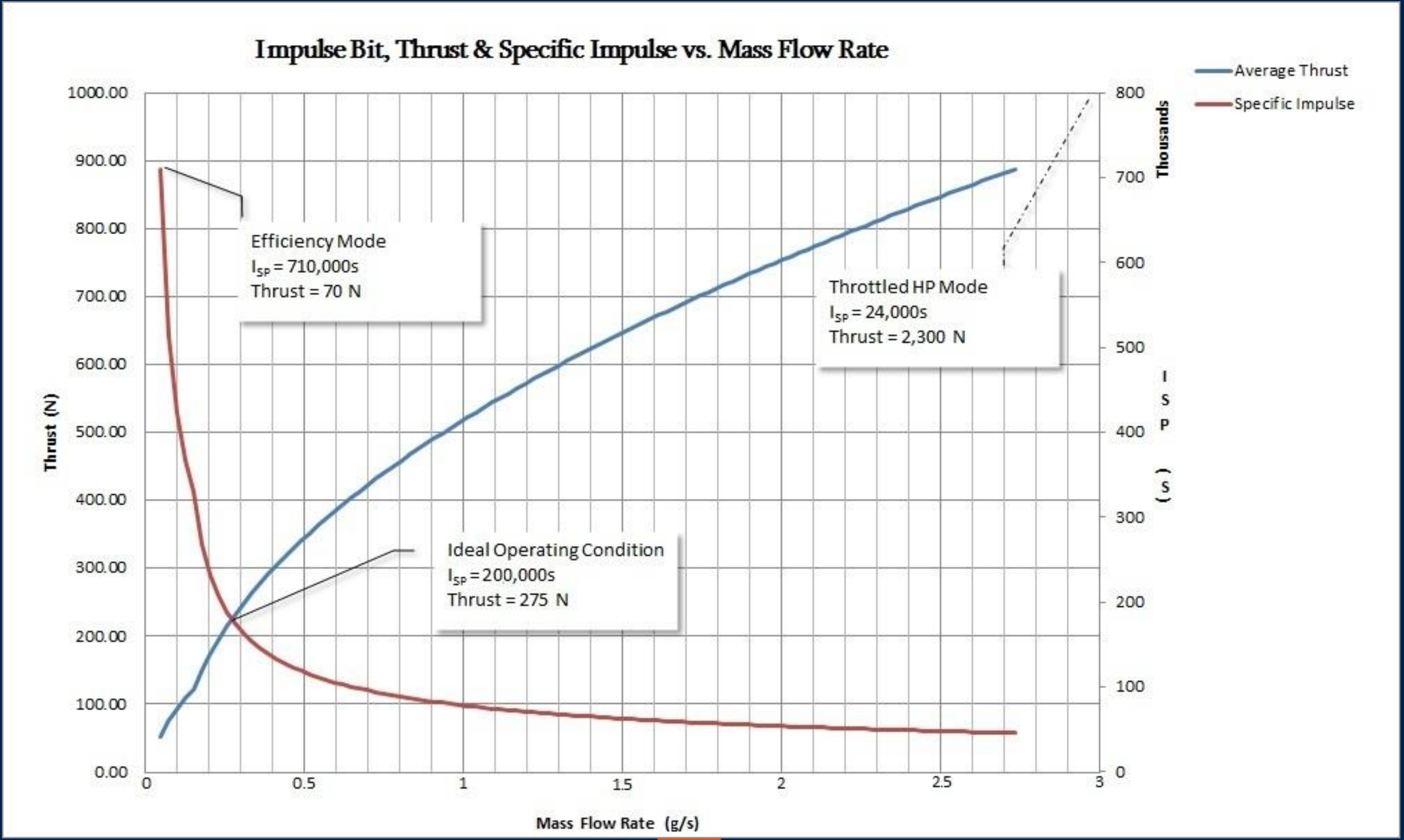
p-^{11}B: Nonradioactive Fusion Power

- Safe, naturally abundant non-radioactive Boron-11 fuel
- Highly charged fusion products (3α @ 8.7 - 9 MeV)
- Aneutronic – minimal shielding from neutron flux required
- Ideal for space-based power systems



System Parameters

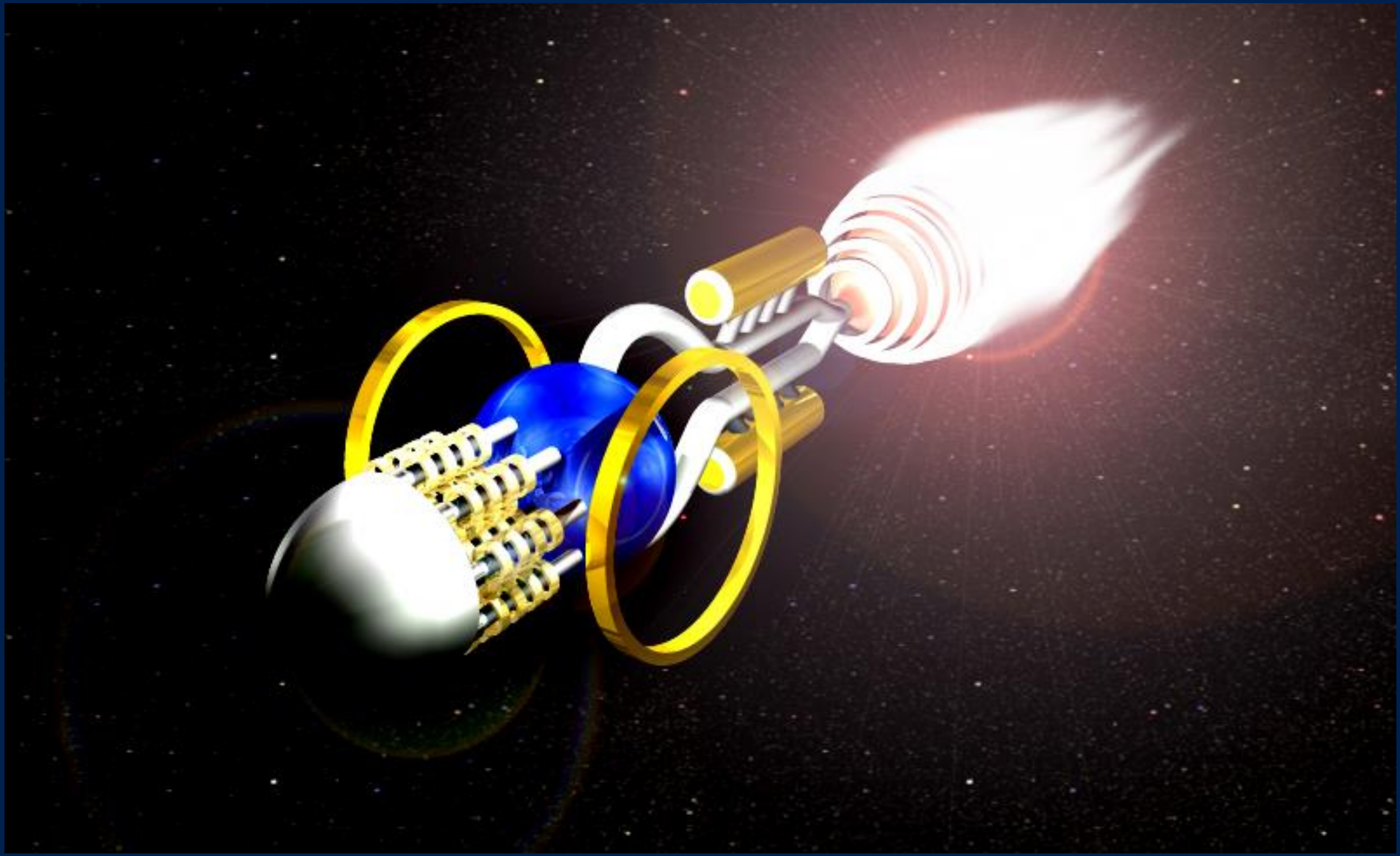
	Power (kW)	Mass (MT)
	Primary Systems	
Helicon Array	1600	2
IEC	18000	8
Magnetic Nozzle	50	1.5
Capture Assembly	100	.5
M_{POW}(Marx, HPDEC, transformers)	-	4.5
	Secondary Systems	
Structure, shielding	-	7
Heat Radiators	1500	4
Injectors, tanks, lines, etc.	<1	.75
Guidance, computers, etc.	<1	.15
Scientific Payload	250	1.5
Total	**21,500**	**29.9**


Impulse Bit, Thrust & Specific Impulse vs. Mass Flow Rate
Average Thrust
Specific Impulse
Thrust (N)
1000.00
900.00
800.00
700.00
600.00
500.00
400.00
300.00
200.00
100.00
0.00
0
0.5
1
1.5
2
2.5
3
Mass Flow Rate (g/s)
800
700
600
500
400
300
200
100
0
Thousands
ISP (s)
Efficiency Mode
Isp = 710,000s
Thrust = 70 N
Throttled HP Mode
Isp = 24,000s
Thrust = 2,300 N
Ideal Operating Condition
Isp = 200,000s
Thrust = 275 N

Conclusion

- *VIPER is an unmanned fusion probe concept*
- *Simple design with fewer assumptions compared to previous manned propulsion concepts*
- *Use of p-^{11}B fuel facilitates aneutronic fusion - hence less mass required for radiation protection*
- *Most of the fusion energy is used for direct thrust conversion*
- *Performance characteristics have been discussed*

Thank you for your attention!



Artist’s conception of VIPER (P. Keutelian, 2012)

References

- Burton, R. L., Momota, H., Richardson, N., Shaban, Y., & Miley, G. H. (2003). Fusion Ship II: A Fast Manned Interplanetary Space Vehicle Uisng Inertial Electrostatic Fusion. *Space Technology and Applications International Forum-STAIF* , 553-562.
- Cox Jr., L. T., Mead Jr., F. B., & Choi, C. K. (1990). Thermonuclear reaction listing with cross-section data for four advanced reactions. *Fusion Technology* , 325-339.
- Hagerty, J., Rogers, J. Spaceship Handbook: Rocket & Spacecraft Designs of the 20th Century – Fictional, Factional and Fantasy. ARA Press, Livermore, CA, 2001.
- Hora, H., Miley, G. H., Ghoranneviss, M., Malekynia, B., Azizi, N., & He, X.-T. (2010). Fusion energy without radioactivity: laser ignition of solid hydrogen-boron (11) fuel. *Energy and Environmental Science* , 479-486.
- Keutelian, Paul. *Viper PFR Fusion System*. September 2011.
- Landau, D. F., & Longuski, J. M. (2006). Trajectories for Human Missions to Mars, Part 2: Low Thrust Transfers. *Journal of Spacecraft and Rockets* , 1043-1047.
- Miley, George H. Fusion Energy Conversion. American Nuclear Society, Urbana, Illinois, 1976.
- Nadler, J. H., Miley, G. H., Coventry, M., Williams, M., Jurczyk, B., Stubbers, R., et al. (n.d.). High-Current Pulsed Operation of an Inertial-Electrostatic Confinement (IEC) Device. Champaign, Illinois, USA.
- Orcutt, John; et al., Viper PFR: Ultra High I_{SP} Pulsed Fusion Rocket, *JBIS*, Submission Pending, 2011.
- Wiebold, M., He, R., & Scharer, J. E. (n.d.). Neutral Depletion and Plasma Flows in a Pulsed High power Helicon Plasma. Madison, Wisconsin, USA.
- Miley, George H , Murali, Krupakar, Inertial Electrostatic Confinement (IEC) Fusion,
- Springer Press, 2014

Thanks for your interest. For further information, contact:

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